

Physical Characteristics of the Spectral States of Galactic Black Holes

Juri Poutanen*, Julian H. Krolik[†] and Felix Ryde[‡]

**Uppsala Observatory, Box 515, SE-75120 Uppsala, Sweden*

[†]Johns Hopkins University, Baltimore, MD 21218

[‡]Stockholm Observatory, SE-13336 Saltsöbaden, Sweden

Abstract. Using simple analytical estimates we show how the physical parameters characterizing different spectral states of the galactic black hole candidates can be determined using spectral data presently available.

SPECTRAL STATES OF GBHC

Galactic black hole candidates (GBHC) radiate in one of several spectral states, and some of them switch suddenly from one state to another. These states can be typified by their extremes: a “hard” state (HS, also called “low”, because of relatively low flux in standard X-ray 2 – 10 keV band), and a “soft” state (SS, a “high” state with relatively strong 2 – 10 keV flux). The broad band spectra in both states can be described as the sum of a blackbody and a power-law with an exponential cut-off. The black body component (probably from the optically thick accretion disk) is more prominent in the SS, when it has a temperature of 0.3 – 1 keV. The lower temperature of the black body in the HS makes it difficult to detect, due to the interstellar absorption. The power-law energy index, α , is 1.0 – 1.5 in the SS, and roughly 0.3 – 0.7 in the HS [1,2]. Recent OSSE observations reveal that the cut-off energy, E_c , of the power-law is correlated with the spectral state; the power-law turns over at ~ 100 keV in the HS, and $E_c \gtrsim 200$ keV in the SS [3,4]. There are also indications of that the amplitude of the Compton reflection “bump” increases when spectrum steepens [2].

The physical nature of the existence of the different spectral states and spectral transitions is not yet completely understood, although a number of models has been proposed (e.g. [5–8]). Recent progress on the theoretical side (we now understand much better how thermal Comptonization works, when the seed photons are produced mainly by reprocessing a part of the hard X-ray output, [11–13]) and the existence of broad band simultaneous spectral data for some of the sources (e.g., [4,9,10]) give us an opportunity to use the observed spectral characteristics in these states to determine the geometry and energy dissipation distribution in

an accreting black hole system. The goal of the present investigation is to infer physical parameters of GBHC purely on the basis of *radiation* physics, this later can be used to guide efforts to obtain *dynamical* explanations for the changes in spectral state. A more detailed discussion can be found in [14].

ANALYTICAL ARGUMENTS

It is natural to attribute the two components with which the spectra are fitted to two physically related regions: an optically thick (quasi-thermal) accretion disk, which is responsible for the blackbody component, and an optically thin hot region (corona), which radiates the hard X-rays. The intrinsic dissipation rates in the “disk” and “corona” are L_s^{intr} and L_h , respectively. The size of the region over which the “disk” radiates most of its energy is R_s , and the size of the corona is R_h .

The hard X-rays are assumed to be produced by thermal Comptonization (e.g. [15]) of the seed photons that are partly created locally (by thermal bremsstrahlung or cyclo-synchrotron radiation [16]) and partly in the quasi-thermal region. The “soft” luminosity, L_s is partly due to local energy dissipation and partly due to reradiation of hard X-rays, created in the “corona”.

The shape of the Comptonized spectrum produced by the “corona” may be described by two parameters: the power-law slope α , and the exponential cut-off energy E_c . Also two parameters (the effective temperature T_s and L_s^{obs}) define the soft part of the radiation. The relative ratio of the observed hard luminosity to the observed soft luminosity, $L_h^{\text{obs}}/L_s^{\text{obs}}$, and the magnitude of the reflection bump (described by the parameter, C , the fraction of solid angle that the optically thick region occupies around the “corona”) complete the set of observables.

These phenomenological parameters are determined by two dimensional quantities, the total dissipation rate and R_s , and four dimensionless physical parameters: the ratio L_s^{intr}/L_h ; the Compton optical depth of the “corona” τ_T ; the fraction D of the light emitted by the thermal region which passes through the “corona”; and the ratio S of intrinsic seed photon production in the “corona” to the seed photon luminosity injected from outside. Another dimensionless parameter, the compactness $l_h \equiv L_h \sigma_T / (m_e c^3 R_h)$, may be used to determine the relative importance of e^\pm pairs in the corona. In this context it is also useful to distinguish the net lepton Compton optical depth τ_p from the total Compton optical depth (including pairs), τ_T .

We will show how all these parameters, as well as several others of physical interest, may be inferred from observable quantities.

Some of the physical parameters of the system may be derived (or at least constrained) almost directly from observables. For example, the electron temperature in the corona (measured in electron rest mass units) is very closely related to the cut-off energy of the hard component:

$$\Theta \simeq f_x E_c / (m_e c^2), \quad (1)$$

where $f_x \sim 0.7$. Similarly,

$$L_h \simeq L_h^{\text{obs}} / \{1 - C[1 - a]\}, \quad (2)$$

where a is the albedo for Compton reflection. The intrinsic disk luminosity is

$$L_s^{\text{intr}} \simeq L_s^{\text{obs}} - CL_h[1 - a]. \quad (3)$$

Taking the local disk emission to be approximately black body, disk's inner radius is

$$R_s \simeq \left\{ L_s^{\text{obs}} / 4\pi\sigma T_s^4 \right\}^{1/2}, \quad (4)$$

where T_s is the effective temperature at the inner edge. A number of correction factors (accounting for difference between color and local effective temperature [17] and incorporating the general relativistic corrections [18] etc.) were omitted in these formulae.

We next employ the two following analytic scaling approximations for thermal Comptonization spectra found by [12]:

$$D(1 + S) = 0.15\alpha^4 L_h / [L_s^{\text{intr}} + CL_h(1 - a)] \quad (5)$$

and

$$\tau_T = 0.16 / (\alpha\Theta). \quad (6)$$

The first expresses how the power-law hardens as the heating rate in the corona increases relative to the seed photon luminosity; the second expresses the trade-off in cooling power between increasing optical depth and increasing temperature.

Finally, both C and D may be written in terms of R_h and R_s . If the corona is a sphere centered on the black hole, and the disk is an annulus of inner radius R_s and infinitesimal vertical thickness,

$$C \simeq R_h / (6R_s) \quad \text{and} \quad D \simeq (1/16)(R_h/R_s)^3. \quad (7)$$

The coefficient in the definition of C is most accurate when the emissivity is uniform within the sphere and it has order unity optical depth; the coefficient in the definition of D assumes the disk surface brightness is $\propto r^{-3}$ and its intensity distribution is isotropic. The relationship between R_h/R_s and C or D is somewhat different in other geometries, but the scaling tends to be similar. Equations (7) may be regarded as giving *independent* estimates of R_h/R_s . If C is used, this ratio is constrained by the observed magnitude of the Compton reflection bump; if D is used, it is determined by the observed hard and soft luminosities, and the slope of the hard X-ray power-law. The corona is assumed roughly spherical.

RESULTS AND CONCLUSIONS

The method described above can be applied to find physical parameters of the system $\Theta, \tau_T, R_s, D(1 + S), R_h/R_s, L_s^{\text{intr}}/L_h^{\text{obs}}$ and l_h from the set of observables $\alpha, E_c, T_s, L_s^{\text{obs}}, C$ and $L_h^{\text{obs}}/L_s^{\text{obs}}$. Unfortunately, existing data are good enough only for a small number of objects. This method applied to Cyg X-1 (see [14]) shows that the inner edge of the cold disk shrinks by roughly a factor of 5 between the hard and soft states (from $\sim 40r_g$ to $\sim 8r_g$, assuming $10 M_\odot$ black hole), while the corona shrinks in radial scale by only factor of two. In the SS, corona covers a sizable portion of the inner disk (see Fig. 1 and [8,9]).

Despite the change in coronal size and luminosity, the compactness of the corona almost does not change during the hard-soft transition. However, its optical depth drops by an order of magnitude from $\sim 1 - 2$ to ~ 0.1 . Electron temperature of the corona is ~ 100 keV in the HS and probably is higher in the SS. In the HS the disk receives only a minority of the dissipation, $L_s^{\text{intr}}/L_h \sim 0.1$, but is the site of most of the heat release in the SS, $L_s^{\text{intr}}/L_h \sim 3$.

Detailed calculations based on the method by [19], that allow us to solve for the energy and electron-positron pair balance together with the self-consistent treatment of the Comptonization in the corona, confirm the conclusions made from simple analytical arguments. We also are able to show that in the case of thermal electrons there are very few e^\pm pairs in the HS, but they can be comparable in number to the net electrons in the SS. In contrast the amount of pairs in the SS can be significant. This means that the fall in τ_p from the HS to the SS is greater than the fall in τ_T .

We close by noting that simultaneous broad band observations from soft X-rays up to gamma-rays are necessary in order to make strong conclusions regarding the

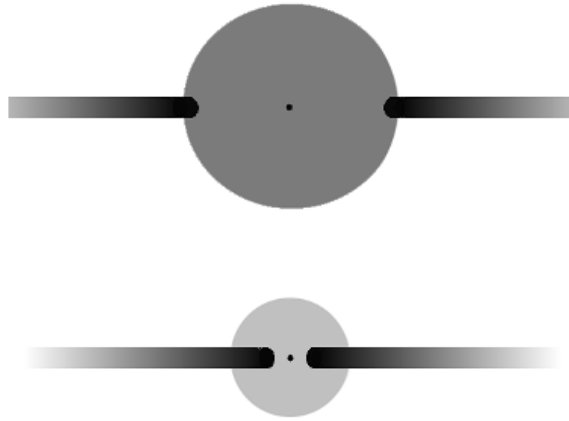


FIGURE 1. Geometry of the accretion flows around black holes in the hard (top) and soft (bottom) states.

geometry and physical conditions in the accretion flows around black hole.

REFERENCES

1. Tanaka, Y., and Levin, W. H. G., “Black-hole binaries” in *X-ray Binaries*, Cambridge: Cambridge University Press, 1995, pp. 126-174.
2. Ebisawa, K., Ueda, Y., Inoue, H., Tanaka, Y., and White, N. E., *ApJ* **467**, 419 (1996)
3. Philips, B. F., Jung, G. V., Leising, M. D. et al., *ApJ* **465**, 907 (1996)
4. Grove J. E. et al., “Two gamma-ray spectral classes of black hole transients” in *The Transparent Universe*, Proc. 2nd INTEGRAL Workshop, ESA SP-382, 1997, pp. 197-200
5. Ichimaru, S., *ApJ* **214**, 840 (1977)
6. Chen, X., and Tamm, R. E., *ApJ* **466**, 404 (1996)
7. Ebisawa, K., Titarchuk, L., and Chakrabarti, S. K., *PASJ* **48**, 59 (1996)
8. Esin, A. A., McClintock, J. E., and Narayan, R., *ApJ* submitted (astro-ph/9705237)
9. Gierliński, M., Zdziarski, A. A., Done, C., Johnson, W. N., Ebisawa, K., Ueda, Y., Haardt, F., Philips, B. F., *MNRAS*, in press
10. Zdziarski, A. A., Johnson, W. N., Poutanen, J., Magdziarz, P., and Gierliński, M., “X-rays and gamma-rays from accretion flows onto black holes in Seyferts and X-ray binaries,” in *The Transparent Universe*, Proc. 2nd INTEGRAL Workshop, ESA SP-382, 1997, pp. 373-380.
11. Ghisellini, G., and Haardt, F., *ApJ* **432**, L95 (1994)
12. Pietrini, P., and Krolik, J. H., *ApJ* **447**, 526 (1995)
13. Stern, B. E., Poutanen, J., Svensson, R., Sikora, M., Begelman, M. C., *ApJ* **449**, L13 (1995)
14. Poutanen, J., Krolik, J. H., and Ryde, F., *MNRAS*, submitted
15. Shapiro, S. L., Lightman, A. P., Eardley, D. N., *ApJ* **204**, 187 (1976)
16. Narayan, R., and Yi, I., *ApJ* **452**, 710 (1995)
17. Shimura, T., and Takahara F., *ApJ* **445**, 780 (1995)
18. Zhang, S. N., Cui, W., and Chen, W., *ApJ* **482**, L155 (1997)
19. Poutanen, J., and Svensson, R., *ApJ* **470**, 249 (1996)